



LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

The Surface Wave Magnitude for the 9 October 2006 North Korean Nuclear Explosion

J.L. Bonner, R.B. Herrmann, D. Harkrider , M.E.
Pasyanos

March 14, 2008

Bulletin of the Seismological Society of America

Disclaimer

This document was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor Lawrence Livermore National Security, LLC, nor any of their employees makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or Lawrence Livermore National Security, LLC. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or Lawrence Livermore National Security, LLC, and shall not be used for advertising or product endorsement purposes.

THE SURFACE WAVE MAGNITUDE FOR THE 9 OCTOBER 2006 NORTH KOREAN NUCLEAR EXPLOSION

A Possible Short Note

Jessie Bonner, Robert B. Herrmann, David Harkrider, and Michael Pasyanos

Paper Contact:

Jessie L. Bonner
4000 S. Medford Suite 10W
Lufkin, TX 75901
936-632-4226
bonner@westongeophysical.com

Submitted to the Bulletin of the Seismological Society of America
Original Submission Date: January 31, 2008
Revisions Submitted: March 12, 2008

ABSTRACT

Surface waves were generated by the North Korean nuclear explosion of 9 October 2006 and recorded at epicentral distances up to 34 degrees, from which we estimated a surface wave magnitude (M_s) of 2.94 with an interstation standard deviation of 0.17 magnitude units. The International Data Centre estimated a body wave magnitude (m_b) of 4.1. This is the only explosion we have analyzed that was not easily screened as an explosion based on the differences between the M_s and m_b estimates. Additionally, this M_s predicts a yield, based on empirical M_s /Yield relationships, that is almost an order of magnitude larger than the 0.5 to 1 kiloton reported for this explosion. We investigate how emplacement medium effects on surface wave moment and magnitude may have contributed to the yield discrepancy.

INTRODUCTION

Accurate estimation of yields for underground nuclear explosions remains an important problem for the nuclear test verification community. This was particularly evident during the days immediately following the announced nuclear test conducted by the Democratic People's Republic of North Korea on 9 October 2006 at 0135 UTC. The Washington Times (13 October 2006) reported that the North Koreans told Chinese officials they were planning to conduct a 4 kiloton (kt) test. After the test was conducted, the yields reported in the media ranged from as small as 0.2 kt to as large as 15 kt based on analyses from different sources. On 16 October 2006, the Office of the United States Director of National Intelligence issued a statement¹ declaring: "Analysis of air samples collected on October 11, 2006 detected radioactive debris which confirms that North Korea conducted an underground nuclear explosion in the vicinity of P'unggye on October 9, 2006. The explosion yield was less than a kiloton."

¹ http://www.odni.gov/announcements/20061016_release.pdf

There are numerous seismic techniques currently used to estimate the yield (Y) of a nuclear explosion, including using body waves (Nuttli, 1986; Nuttli, 1988; Patton, 1988; Vergino and Mensing, 1990; Ringdahl *et al.*, 1992; Murphy and Barker, 2001) and scattered coda waves (Mitchell, 1991; Murphy *et al.*, in review). For example, Walter *et al.* (2007) showed that the regional *P*-wave source spectra for the North Korea (NK) explosion suggested an explosion of 0.5 kt at 100 meters depth. John R. Murphy (pers. Comm.) estimated 1 kt using teleseismic network-average *P*-wave spectra, while Kværna *et al.* (2007) used body wave magnitude (m_b) /Yield relations to estimate a yield between 0.5 – 1 kt. Kim and Richards (2007) also estimate the yield at 0.6 kt based on an m_b /Yield relationship.

Surface wave magnitudes (M_s) have also been used to estimate the yields of underground nuclear explosions (Marshall *et al.*, 1979; Bache, 1982; Sykes and Cifuentes, 1984; Woods and Harkrider, 1995; Stevens and Murphy, 2001). Bache (1982) reported that M_s /log Y relationships should provide accurate results for large events; however, increased uncertainty in the estimated yields was possible due to Rayleigh-wave radiation patterns associated with tectonic release and secondary source effects from explosions. An additional problem for smaller explosions was that fewer M_s observations would be available to estimate the yields.

Bonner *et al.*, (2003) showed that surface wave magnitude estimation at 7-seconds period, instead of the conventional 17 to 23 second period range, could increase the number of M_s observations for small events at regional distances. These results led to the development of a time-domain method for measuring surface waves (Russell, 2006) with minimum digital processing using zero-phase Butterworth filters at regional and teleseismic distances. The method can effectively measure surface wave magnitudes at variable periods between 8 and 25 seconds. For applications over typical continental crusts, the magnitude equation is:

$$M_{s(b)} = \log(a_b) + \frac{1}{2} \log(\sin(\Delta)) + 0.0031 \left(\frac{20}{T} \right)^{1.8} \Delta - 0.66 \log\left(\frac{20}{T}\right) - \log(f_c) - 0.43, \quad (1)$$

where a_b is the amplitude of the Butterworth-filtered surface waves (zero-to-peak in nanometers) and $f_c \leq \frac{0.6}{T\sqrt{\Delta}}$ is the filter frequency of a two-pass phaseless third-order Butterworth band-pass filter with corner frequencies $1/T-f_c$, $1/T+f_c$. At the reference period $T = 20$ seconds, the equation is equivalent to Von Seggern's formula (1977) scaled to the Vaněk *et al.* (1962) formula at 50 degrees. For periods $8 \leq T \leq 25$ s, the equation is corrected to $T = 20$ seconds to account for source effects, attenuation, and dispersion. Bonner *et al.* (2006a) refer to this technique as $M_s(\text{VMAX})$ for Variable-period, MAXimum amplitude magnitude estimates.

There are several advantages to the $M_s(\text{VMAX})$ method. First, the technique allows for time domain measurements of surface wave amplitudes, giving an analyst the ability to visually identify the phase of interest. It also allows for surface wave magnitudes to be measured at some local and regional distances where traditional 20-second magnitudes cannot be used. And the local and regional distance magnitude estimates are not biased with respect to teleseismic estimates using the $M_s(\text{VMAX})$ measurement technique. Additionally, the application of narrow-band Butterworth filtering techniques appropriately handles Airy phase phenomena that, prior to this technique, had to be accounted for using Marshall and Basham's (1972) empirical path corrections. Finally, because the method is variable period and not restricted to near 20-seconds period, the analyst is allowed to measure M_s where the signal is largest.

We have applied the $M_s(\text{VMAX})$ measurement technique to the surface waves generated by the 9 October 2006 North Korean nuclear test. In the following sections of this manuscript, we present the data used to estimate a network surface wave magnitude. This estimate is then compared to the m_b and used to estimate a yield based on empirical $M_s/\log(Y)$ relationships.

ANALYSIS

Data

The Incorporated Research Institutions in Seismology (IRIS) dedicated a data download page to the 9 October 2006 North Korean (NK) event. The data were corrected for the instrument response and converted to displacement in nanometers. Data from KSRS were obtained from the US National Data Center and were corrected to displacement using the frequency-amplitude-response file. The horizontal components were rotated into radial and transverse waveforms. Examples of the data for three stations are shown in Figure 1. At these distances, there are large amplitude Rayleigh wave arrivals observed on the radial and vertical components. There was no significant Love wave energy in the surface wave analysis window.

Magnitude Estimation

The results of the M_s (VMAX) analysis for seismic stations within 34 degrees of the NK event are summarized in Figure 2 and Table 1. We are confident that Rayleigh waves were observed at INCN, ENH, TLY, HIA, BJT, MDJ, ERM, MAJO, and KS31 based on dispersion and particle motion tests. We observed longer period (>20 sec) surface waves at MKAR, LSA, and CHTO. We were unable to identify Rayleigh waves at NACB, YULB, YAK, MA2, YSS, and PET; however, we did calculate a noise-based M_s (VMAX) at each of these stations (Figure 2). The concept behind the noise-based measurement is that had an estimate been possible at this station, it would have been smaller than the noise-based M_s (VMAX) and thus is similar to a maximum-likelihood magnitude (McLaughlin, 1988).

We estimated a network surface wave magnitude of 2.94 with interstation standard deviation of 0.17 magnitude units (m.u.). Selby (2007) estimated the surface wave magnitude for this event as 2.83 using the Marshall and Basham (1972) formula, which is typically 0.10

m.u. smaller than $M_s(\text{VMAX})$ as will be discussed later in this paper.

We note that much of the scatter in our measurement is related to three large magnitude estimates at stations ENH, BJT, and TLY, all of which are from westerly event-to-station azimuths (see Figure 2). While a Rayleigh-wave radiation pattern could cause this azimuth effect, there were no Love waves observed on any of our data to corroborate anisotropic source effects. Furthermore, there are additional stations along similar azimuths (e.g., HIA, CHTO, MKAR) that did not exhibit the increased magnitudes. Stevens *et al.* (2007) also found increased magnitudes at ENH, BJT, and TLY and had some success explaining the magnitudes using path corrections.

The International Data Center (IDC) reported an m_b of 4.1 for the NK event (Richards, 2007). We compared our magnitude to previous $M_s:m_b$ research (Bonner *et al.*, 2006a,b) for Eurasia and found the NK event plots slightly above the Murphy *et al.* (1997) event screening value, which is $M_s=2.90$ for an IDC m_b of 4.1. The NK event is the only nuclear explosion we have analyzed with a network $M_s(\text{VMAX})$ that does not fall into the explosion population below the $M_s:m_b$ screening line. We do note that some mining explosions do not discriminate well because of the reduced P -wave amplitudes associated with delay-firing practices (Bonner *et al.*, 2006b). Some have suggested the North Korean results could be evidence of a convergence of the earthquake and explosion $M_s:m_b$ populations at small magnitudes (as postulated in Stevens and Day, 1985); however, Bonner *et al.* (2006a) saw no evidence of the convergence at the Nevada Test Site (NTS) for events of similar and smaller m_b . Others have suggested this is further evidence of the need to revise the current screening criteria used for earthquake and explosion identification.

Yield Estimation

Since the 9 October 2006 event was the first nuclear explosion conducted at the NK test site, there is no calibrated empirical M_s vs. Yield formula that can be used to estimate the event yield. Instead, we considered a series of published $M_s/\log Y$ relations for different test sites from previous researchers (e.g., Bache, 1982; Stevens and Murphy, 2001). While there are other similar empirical relationships in the literature (e.g., Sykes and Cifuentes, 1984; Woods, 1993), we chose Bache (1982) and Stevens and Murphy (2001) because they employed the Marshall and Basham (1972) and Rezapour and Pearce (1998) formulas, respectively, to estimate surface wave magnitudes. We have developed conversion factors that relate $M_s(\text{VMAX})$ to both formulas (Bonner *et al.*, 2006a). For example, $M_s(\text{VMAX})$ estimates are on average 0.18 m.u. larger than those of Rezapour and Pearce (1998) and 0.10 m.u. larger than those of Marshall and Basham (1972). Using these values, we were able to convert the Bache (1982) and Stevens and Murphy (2001) $M_s/\log Y$ relationships into an $M_s(\text{VMAX})/\log Y$ relationship (Figure 4).

Using the $M_s(\text{VMAX})/\log Y$ relationships in Figure 4 and the $M_s(\text{VMAX})$ estimated for the NK nuclear test, we find a range of yields between 3 and 10 kt. The median yield is 5.6 kt. These yields are significantly larger than the sub kiloton results from P -wave based measurements. Even if we assume the three largest $M_s(\text{VMAX})$ estimates (ENH, BHT, TLY) are enhanced by unmodeled path effects and subsequently remove them from our analysis, our median yield estimate is reduced to 4.5 kt.

DISCUSSION AND CONCLUSIONS

The large surface wave magnitude estimated for the NK explosion results in a yield estimate that is not in agreement with results from P -wave studies. The $M_s(\text{VMAX})$ for the NK event is also greater than expected when compared with earthquakes in the region of similar moment. We estimated $M_s(\text{VMAX})$ for 28 earthquakes occurring on or near the Korean

Peninsula using local and regional seismic data and then regressed the results (Figure 5) against moments estimated by Koper *et al.* (2008). The $M_s(\text{VMAX}) \pm 1\sigma$ for the NK event falls outside of the 95% confidence band for the earthquake moment-magnitude regression. While this may be a depth effect, it is further evidence of the unique characteristics of the surface wave magnitude for this explosion. In this section, we present a scenario in which a small yield explosion in a high-velocity emplacement medium could generate a relatively large M_s estimate.

Denny and Johnson (1991) developed a model for the measured seismic moment (M_o) of explosions:

$$M_o = \frac{1}{311} M_t P_o^{0.3490} 10^{-0.0269 GP}, \quad (2)$$

where GP is gas porosity and P_o is overburden pressure ($P_o = \rho gh$). M_t is the theoretical moment and is defined as:

$$M_t = \frac{4}{3} \pi \rho \alpha^2 R_c^3, \quad (3)$$

where α is the P -wave velocity and R_c is the cavity radius estimated by:

$$R_c = \frac{1.47 \times 10^4 Y^{\frac{1}{3}}}{\beta^{0.3848} P_o^{0.2625} 10^{0.0025 GP}}. \quad (4)$$

From the equations above, we can see that the measured moment for explosions in the Denny and Johnson (1991) model depends on the P -wave and S -wave (β) velocities and yield (Y).

NTS velocities provided by Springer *et al.* (2002) show typical emplacement P -wave velocities (α) of 3.2 km/sec (Pahute), 2.7 km/sec (Rainier), 2.4 km/sec (Yucca below the water table), and 1.7 km/sec (Yucca above the water table). Ferguson (1988) suggests the S -wave velocities (β) are typically between 0.45α to 0.53α . While similar published data do not exist for the NK test site, the Korean seismic model of Herrmann *et al.* (2005) suggest P -wave velocities

in the mountainous region around the test site are ~ 5 km/sec with S -wave velocities of ~ 3 km/sec.

We programmed the Denny and Johnson (1991) model (Equations 2-4) in order to investigate the relationship between changes in the material properties, yield, and depth of burial on the seismic moment estimates. Two velocity models were considered for the upper kilometer—a generic NTS model characterized by a density of 2 g/cm^3 , P -wave velocity of 2 km/sec, and S -velocity of 1 km/sec and a Korean model with a density of 2.5 g/cm^3 , P -wave velocity of 5.1 km/sec, and an S -wave velocity of 3 km/sec. We included the NTS model because the Denny and Johnson (1991) data set consisted of many events from the NTS and it is a well-used reference model for explosions.

The moments calculated for these two models are presented in Figure 6 as a function of depth of burial and yield. Also shown is the isotropic moment ($M_I = 3.10 (\pm 0.62) \times 10^{14} \text{ N-m}$) for the NK event estimated by Koper *et al.*, (2008). These two plots show the importance of shot emplacement media, in addition to expected depth of burial, on the surface wave moments generated from explosions with similar yields.

It is possible to convert the moments in Figure 6 to surface wave magnitudes (M_s). For example, Stevens and McLaughlin (2001) use $M_s = \log Mo' - 11.74 (\pm 0.21)$ to convert their path-corrected scalar moment ($\log Mo'$ in N-m) to an M_s . To convert from moment to $M_s(VMAX)$, we first generated explosion synthetics using the Herrmann (2006) codes at depths between 0.1 and 1 km with a fixed moment and measured the resulting synthetic $M_s(VMAX)$. This resulted in:

$$M_s(VMAX) = \log M_o - 11.8. \quad (5)$$

We note that the depth effects for a fixed-moment explosion in the upper 1 km on the surface wave magnitudes are insignificant. Secondly, we used five Asian nuclear explosions for which we had estimates of $M_s(VMAX)$ and isotropic moment to determine a similar constant for Equation 5 (e.g., 11.79 versus 11.80).

We converted the moments in Figure 6 to $M_s(VMAX)$ using Equation 5, and then highlighted our surface wave magnitude estimate for the NK explosion in Figure 7. We note that the yields for the NTS model and our $M_s(VMAX)$ estimated yields agree with the historical data presented in Figure 4. Figure 7 predicts that for a fast velocity (e.g., hard rock) test site, it is possible for a lower yield explosion to produce larger $M_s(VMAX)$ estimates than our current empirical $M_s/\log Y$ relationships would predict. While these yield estimates are still not in the sub kiloton range, they are within a factor of 2-3 of the reported yield for depths of burial less than 500 m.

Other fast velocity test sites, such as Lop Nor (China) and Degelen Mountain (Kazakhstan), have explosion-generated surface waves that are easily discriminated by $M_s:m_b$, including some of the explosions plotted in Figure 3. Thus, the fast velocity emplacement media may not be the only explanation for the inadequate $M_s:m_b$ screening and overestimated yield of the 9 October 2006 event. For example, Patton (2008) has postulated that the anomalous large M_s for the North Korean test could be due to the complete absence of tensile failure for this event.

In summary, we have determined stable surface wave magnitudes for regional earthquakes in the Korean Peninsular region and also showed the application of $M_s(VMAX)$ to the North Korean nuclear explosion. The resulting NK magnitude was unusually large when compared with the body wave magnitude and estimated seismic moment for the event, and

resulted in an overestimated yield when considering historical $M_s/\log Y$ relationships. However, modeling the M_s using the Denny and Johnson (1991) explosion model in hard rock helped explain the overestimated yield and highlights the importance of knowing the near-surface velocity structure when estimating the yield of buried explosions.

ACKNOWLEDGEMENTS

We wish to thank Ana Stroujkova and Delaine Reiter for help acquiring some of these waveform data. Also, we have had helpful discussions with Mark Woods, Leigh House, Keith Koper, Jeff Stevens, Neil Selby, David Bowers, and Kevin Mayeda regarding manuscript preparation and the interpretation of these results. We thank IRIS and the USNDC for access to their data for this event. This research was sponsored by the National Nuclear Security Administration Office of Nonproliferation Research and Development and Office of Defense Nuclear Nonproliferation under Contract No. DE-AC52-04NA25547.

REFERENCES

- Bache, T. (1982). Estimating the yield of underground nuclear explosions, *Bull. Seism. Soc. Am.*, **72**, S131-S168.
- Bonner, J., D. Harkrider, E.T. Herrin, R.H. Shumway, S.A. Russell and I.M. Tibuleac (2003). Evaluation of short-period, near-regional M_s scales for the Nevada Test Site, *Bull. Seism. Soc. Am.*, **93**, 1,773-1,791.
- Bonner, J. L., D. Russell, D. Harkrider, D. Reiter, and R. Herrmann (2006a). Development of a time-domain, variable-period surface wave magnitude measurement procedure for application at regional and teleseismic distances, Part II: application and $M_s - m_b$ performance. *Bull. Seism. Soc. Am.*, **96**, 678 – 696.

This work was performed under the auspices of the U. S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-ENG-48.

- Bonner, J.L. M. Pasyanos, M. Leidig, H. Hooper, and D. Harkrider, (2006b). A comparison of different surface wave magnitude measurement procedures on a Eurasian dataset. *Proceedings of the 2006 Seismic Research Review* Orlando, Fl.
- Denny, M.D. and L. R. Johnson (1991). The explosion seismic source function: model and scaling laws revisited, in H.J. Patton and P.G. Richards, Eds., *Explosion Source Phenomenology*, Geophysics Monograph 65, American Geophysical Union, Washington, pp 1-24.
- Ferguson, J.F. (1988). Body-wave magnitude variation at Yucca Flat, Nevada *Bull. Seism. Soc. Am.*, **78**, 863-872.
- Herrmann, R.B., Y.S. Jeon, and H.J. Yoo (2005). Broadband source inversion using digital data from Korean seismic networks, in *Proceedings: 4th International Seminar on Seismic Tomography of Far-East Asia and Related words*, December 2, 2005, Korea Institute of Geoscience and Mineral Resources, Daejeon, Korea.
- Herrmann, R.B. (2006). *Computer Programs in Seismology*, Version 3.30, St. Louis University.
- Kim, W.Y. and P. G. Richards (2007). North Korean nuclear explosion on 9 October 2006: a practical example of seismic discrimination at low yield. *Abs. Seism. Res. Letts.*, **78**, p. 253.
- Koper, K., R. B. Herrmann, and H.M. Benz (2008). Overview of open seismic data from the North Korean event of 9 October 2006, *Seism. Res. Letts.*, **79**, 208-216.
- Kværna, T. F., Ringdahl, and U. Baadshaug (2007). North Korean's nuclear test: the capability for seismic monitoring of the North Korean Test Site. *Seism. Res. Letts.*, **78**, 487-497.
- Marshall, P.D. and P.W. Basham (1972). Discrimination between earthquakes and underground explosions employing an improved Ms scale, *Geophys. J. R. Astr. Soc.*, **29**, 431-458.

- Marshall, P.D., Springer, D.L, and Rodean, H.C. (1979). Magnitude corrections for attenuation in the upper mantle, *Geophys. J. R. Astr. Soc.*, **57**, 609-638.
- McLaughlin, K. (1988). Maximum-likelihood event magnitude estimation with bootstrapping for uncertainty estimation, *Bull. Seism. Soc. Am.*, **78**, 855-862.
- Mitchell, B. J., (1991). Yield and discrimination studies in stable continental regions, St. Louis University Final Report.
- Murphy, J. R., B. W. Barker, and M. E. Marshall, (1997). Event screening at the IDC using the *Ms/mb* discriminant. *Maxwell Technologies Final Report*. 23 p.
- Murphy, J. R. and B. W. Barker (2001). Application of network-averaged teleseismic *P*-wave spectra to seismic yield estimation of underground nuclear explosions. *Pure. Appl. Geophys.*, **158**, 2123-2171.
- Murphy, K. R., K. Mayeda, and W. R. Walter (2007). Coda Spectral Peaking for Nevada Nuclear Test Site Explosions, submitted to *Geophys. Res. Letts*.
- Nuttli, O. ,(1986). *Lg* magnitudes of selected East Kazakhstan underground explosions, *Bull. Seism. Soc. Am.* **78**, 1,241 – 1,251.
- Nuttli, O. (1988). *Lg* magnitudes and yield estimates for underground Novaya Zemlya nuclear explosions, *Bull. Seism. Soc. Am.* **78**, 873-884.
- Patton, H. J., (1988). Application of Nuttli's method to estimate yield of Nevada Test Site explosions recorded on Lawrence Livermore National Laboratory's Digital Seismic System, *Bull. Seism. Soc. Am.*, **78**, 1759-1772.
- Patton, H. J., (2008). Implications of the CLVD on long-period seismic waves from nuclear explosions. To be published as an abstract in *Seism. Res. Letts*.

- Rezapour, M., and R.G. Pearce (1998). Bias in surface-wave magnitude M_s due to inadequate distance correction, *Bull. Seism. Soc. Am.*, **88**, 43-61.
- Richards, P. (2007). Forensic seismology and CTBT verification, *CTBTO Newsletter*, **9**, p 1.
- Ringdahl, F., P. D. Marshall, and R. W. Alewine (1992). Seismic yield determination of Soviet underground nuclear explosions at the Shagan River test site, *Geophys. J. Int.*, **109**, 65–77.
- Russell, D.R. (2006). Development of a time-domain, variable-period surface wave magnitude measurement procedure for application at regional and teleseismic distances, Part I: Theory, *Bull. Seism. Soc. Am.*, **96**, 665 - 677.
- Sykes, L. R. and I.L. Cifuentes (1984). Yields of Soviet underground nuclear explosions from seismic surface waves: Compliance with the Threshold Test Ban Treaty, *Proc. Natl. Acad. Sci. USA* **81**, pp. 1922-1925,
- von Seggern, D. (1977). Amplitude distance relation for 20-Second Rayleigh waves. *Bull. Seism. Soc. Am.*, **67**, 405-411.
- Selby, N. (2007). Implications of the 9 October 2006 North Korean nuclear test for event screening. *Abs. Seism. Res. Letts.*, **78**, p. 253.
- Springer, D. L., G. A. Pawloski, J. L. Ricca, R. F. Rohrer, and D. K. Smith (2002). Seismic source summary for all U.S. below-surface nuclear explosions, *Bull. Seism. Soc. Am.*, **92**, 1806–1840.
- Stevens, J. L. and S. M. Day (1985). The physical basis of the $m_b:M_s$ and variable frequency magnitude methods for earthquake/explosion discrimination, *J. Geophys. Res.*, **90**, 3009-3020.

- Stevens, J. L. and K.L. McLaughlin (2001). Optimization of surface wave identification and measurement, in *Monitoring the Comprehensive Nuclear Test Ban Treaty: Surface Waves*, eds. Levshin, A. and M.H. Ritzwoller, *Pure Appl. Geophys.*, **158**, 1,547-1,582.
- Stevens, J. L. and J.R. Murphy (2001). Yield Estimation from Surface-wave Amplitudes, in *Monitoring the Comprehensive Nuclear Test Ban Treaty: Surface Waves: Source Processes and Explosion Yield Determination*, eds. Ekstrom, G., M. Denny, and J.R. Murphy, *Pure Appl. Geophys.*, **158**, 2,227-2,251.
- Stevens, J., J. Given, H. Xu, and G. Baker, (2007). Development of Surface Wave Dispersion and Attenuation Maps and Improved Methods for Measuring Surface Waves, Proceedings of the 29th Monitoring Research Review. Denver, CO. 25-27 September, 2007.
- Vanek, J., A. Zatopek, V. Karnik, Y.V. Riznichenko, E.F. Saverensky, S.L. Solov'ev, and N.V. Shebalin, (1962). Standardization of magnitude scales. *Bull. (Izvest.) Acad. Sci. U.S.S.R., Geophys. Ser.*, 2, 108.
- Vergino, E.S. and Mensing, R.W. (1989). Yield estimation using regional $m_b(Pn)$, *Lawrence Livermore National Laboratory Report UCID-101600*.
- Walter, W., E. Matzel, M. Pasyanos, D. Harris, R. Gok, and S. Ford, (2007). Empirical observations of earthquake-explosion discrimination using P/S ratios and implications for the sources of explosion S -Waves, Proceedings of the 29th Monitoring Research Review. Denver, CO. 25-27 September, 2007.
- Woods, B. B. and D. G. Harkrider (1995). Determining surface-wave magnitudes from regional Nevada Test Site, *Geophys. J. Int.* **120**, 474-498.
- “Korean Test Seen as Only Partial Blast,” *Washington Times*, October 13, 2006.

“Statement by the Office of the Director of National Intelligence on the North Korea Nuclear Test,” Office of the Director of National Intelligence Press Release, October 16, 2006.
(http://www.odni.gov/announcements/20061016_release.pdf)

AUTHOR AFFILIATIONS

Jessie L. Bonner (Manuscript Contact)

Weston Geophysical Corporation
4000 S. Medford Suite 10W
Lufkin, TX 75901
936-632-4226 (phone and fax)
bonner@westongeophysical.com

David Harkrider

Weston Geophysical Corporation
57 Bedford Street Suite 102
Lexington, MA 02420
hark@ourconcord.net

Robert B. Herrmann

Department of Earth & Atmospheric
Sciences,
Saint Louis University
3642 Lindell Boulevard
St. Louis, MO 63108
TEL: 314 977 3120
rbh@eas.slu.edu

Michael Pasyanos

Lawrence Livermore National Laboratory
7000 East Ave. MS L-205
Livermore, CA 94551-0808
925-423-5835
Fax 925-423-4077
pasyanos1@llnl.gov

TABLE CAPTIONS

Table 1. M_s (VMAX) Results for the 9 October 2006 North Korean event.

FIGURE CAPTIONS

Figure 1. Three-component recordings of surface waves recorded from the 9 October 2006 North Korean event. The waveforms have been rotated to provide the transverse, radial, and vertical components at stations a) MDJ, b) BJT, and c) ENH. The vertical lines in each subplot represent surface wave analysis group velocity windows of 4.0 and 2.5 km/sec.

Figure 2. Signal- and noise-based M_s (VMAX) estimates for the NK nuclear test. a) Map of stations showing where noise-based (open circles) and signal-based (solid circles) surface wave magnitudes were estimated. b) Station magnitudes show a network average of

2.94, which considers only signal-based (solid circle) measurements.

Figure 3. Network M_s (VMAX) estimates for earthquakes and nuclear explosions in Eurasia (from Bonner et al., 2006b). The NK event is plotted as a star and falls slightly above the Murphy *et al.* (1997) screening line. The m_{bs} are from the IDC.

Figure 4. $M_s/\log Y$ relationships for different nuclear test sites. The Bache (1982) and Stevens and Murphy (2001) relationships were calibrated to M_s (VMAX) using correction terms estimated in Bonner *et al.* (2006a). The gray region represents the estimated M_s (VMAX) for the NK explosion $\pm 1 \sigma$.

Figure 5. Regression of seismic moment versus surface wave magnitude M_s (VMAX) for earthquakes in the Yellow Sea and Korean Peninsula (YSKP) region. Also shown is the 9 October 2006 NK explosion. The solid line is the regression while the dashed lines represent the 95% confidence band on the expected surface wave magnitude value. Error bars on the explosion data point show $\pm 1 \sigma$.

Figure 6. Estimated moments for explosions using the Denny and Johnson (1991) source model as a function of yield and depth of burial for a) NTS and b) Korean models. The dashed line shows the isotropic moment ($M_I = 3.10 (\pm 0.62) \times 10^{14}$ N-m) for the NK event estimated by Koper *et al.*, (2008).

Figure 7. Yield estimates as a function of depth for the observed M_s (VMAX) estimate for two velocity models (NTS and Korea). The shaded regions reflect the variability due to the $\pm 1 \sigma$ on the observed magnitude.

TABLES

Table 1.

Station	Distance (deg)	Period	$M_s(VMAX)$
MDJ	3.32	8	2.77
KS31	3.98	10	2.71
INCN	4.28	10	2.85
MAJO	8.53	20	2.82
BJT	9.92	12	3.16
HIA	10.33	8	2.97
ERM	10.53	11	2.93
ENH	19.31	13	3.2
TLY	20.26	15	3.23
LSA	32.76	23	2.91
MKAR	33.67	23	2.81
CHTO	34.14	20	2.89

FIGURES

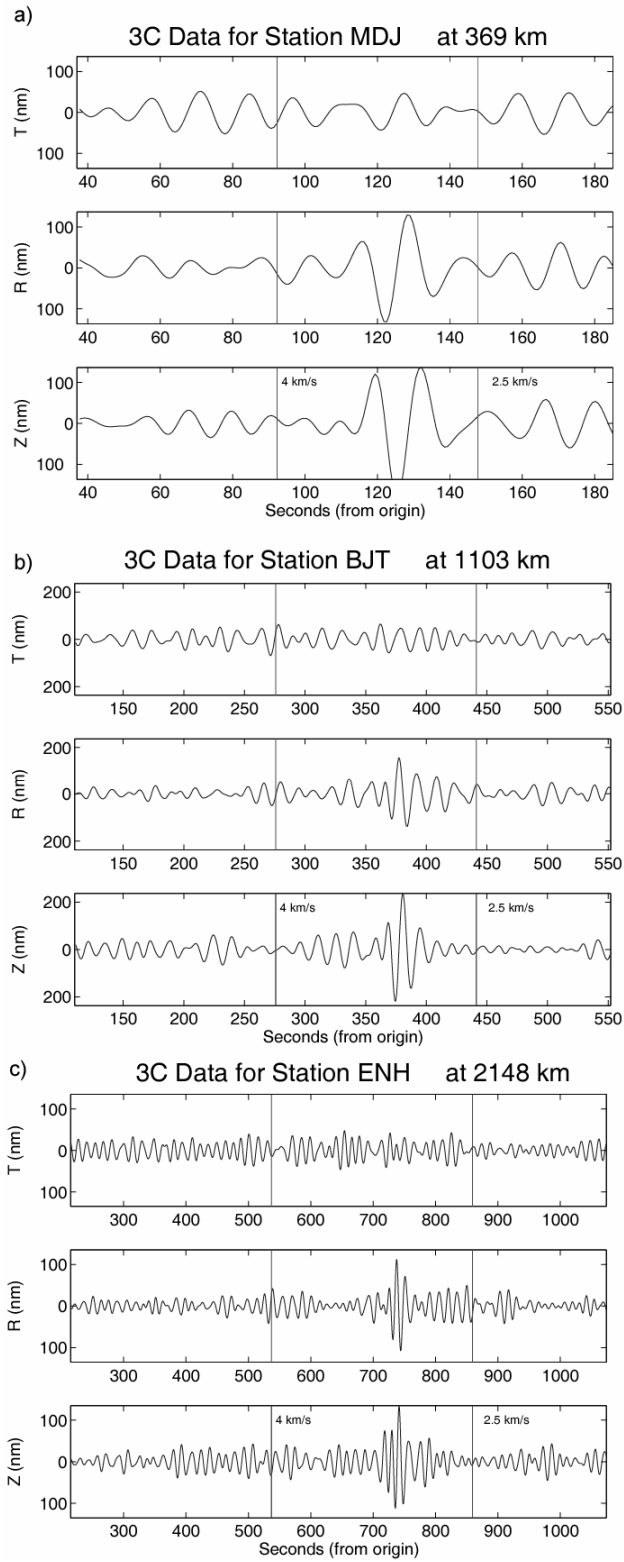


Figure 1. (Bonner *et al.*) ↑

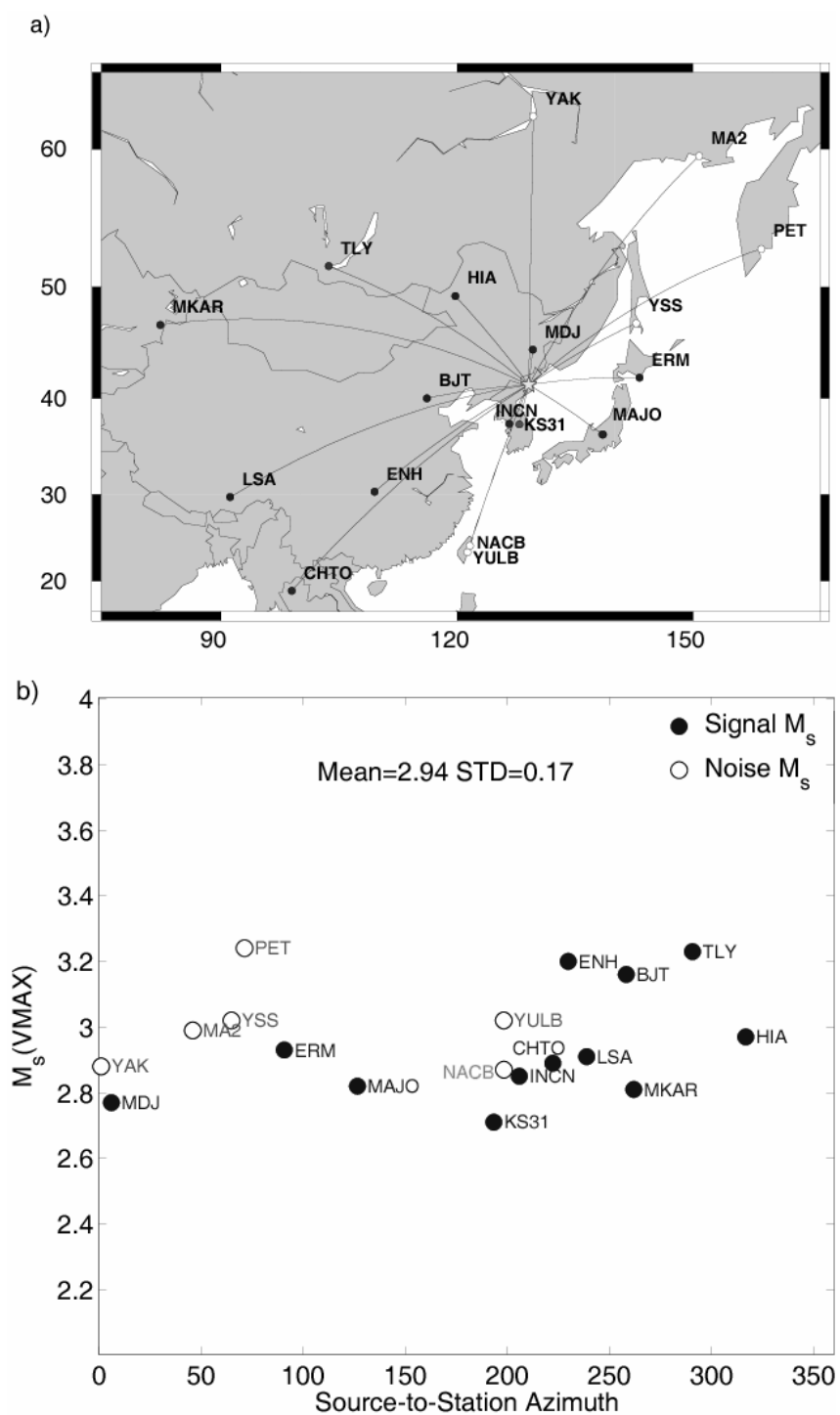


Figure 2. (Bonner *et al.*) ↑

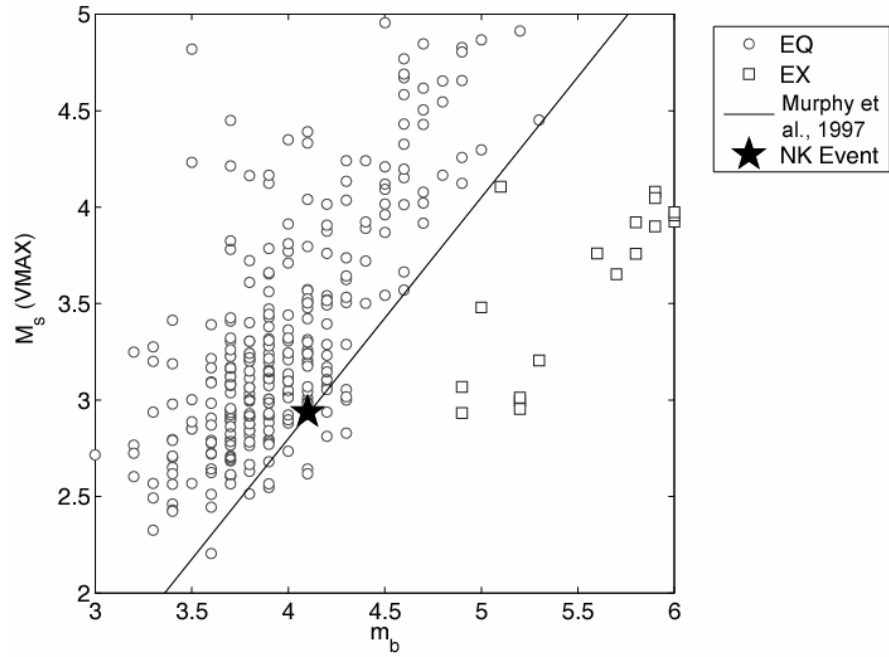


Figure 3. (Bonner *et al.*) ↑

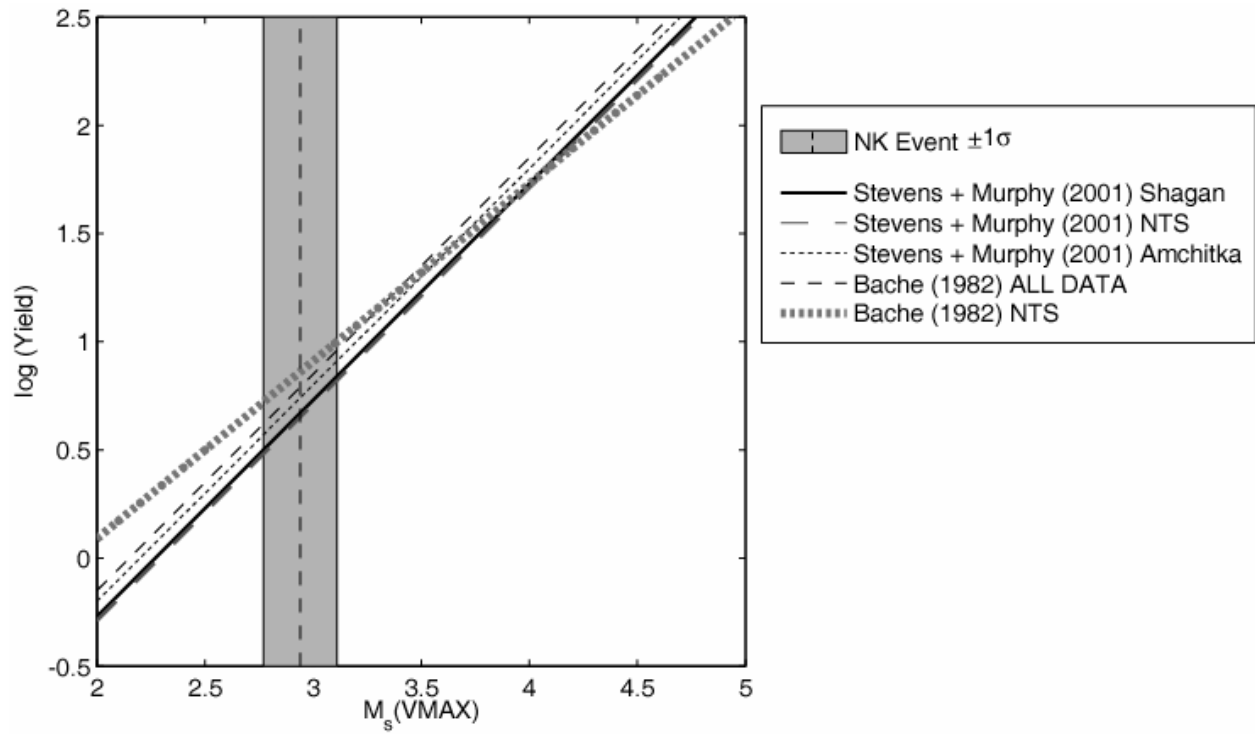


Figure 4. (Bonner *et al.*) ↑

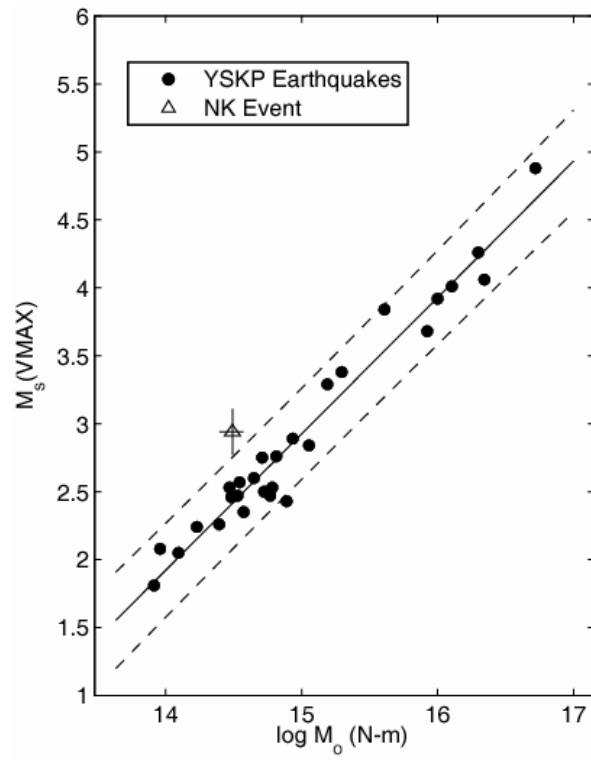


Figure 5. (Bonner *et al.*) ↑

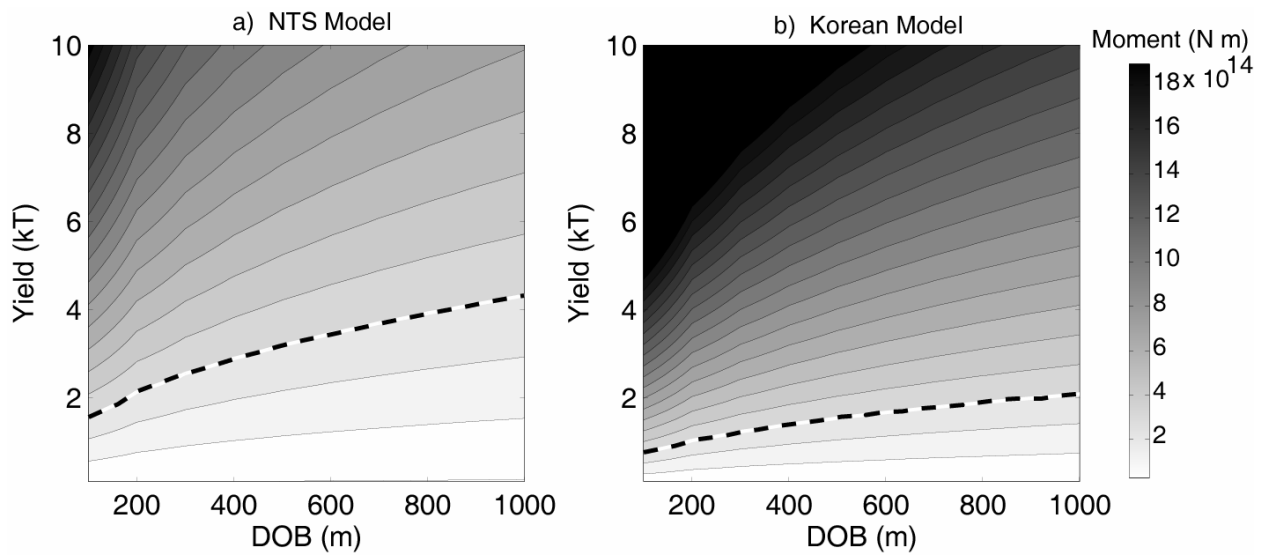


Figure 6. (Bonner *et al.*) ↑

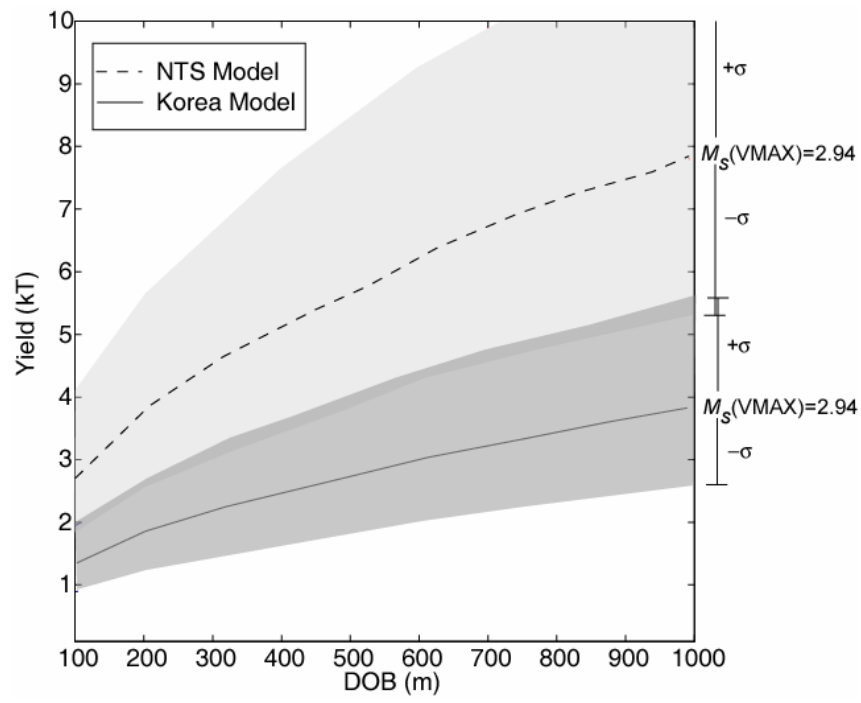


Figure 7. (Bonner *et al.*) ↑